

Muon-Electron Conversion



 $(\mu 2e)$

at FNAL

R. Bernstein FNAL NP'08 6 March 2008





Collaboration

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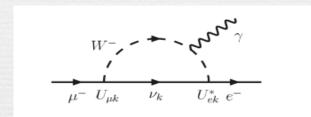
many MECO
collaborators with
considerable
kahn, knowledge



Motivation



- ν's have mass! Therefore individual lepton numbers are not good quantum numbers
- Therefore occurs in Charged Leptons as well



Except neutrinos have to change flavor in loop...

$$BR(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U_{\mu i}^* U_{ei} \frac{\Delta m_{1i}^2}{M_W^2} \right| < 10^{-54}$$

But this is good! New physics not hidden by boring old neutrino oscillations

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Major Contributions



Standard Model

SuperSymmetry

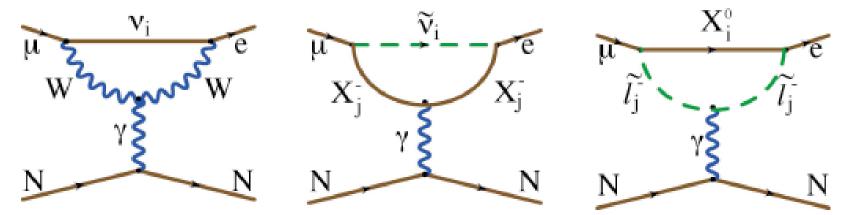


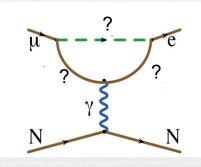
Figure 1.1: The leading Standard Model diagram for $\mu+N \rightarrow e+N$ is shown on the left. The center and right figures are the dominant SUSY diagrams.

- Supersymmetry
- Far Higher than LHC, > 1000 TeV

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\Rightarrow μ Conversion and $\mu \rightarrow e\gamma$

Dipole/Penguin

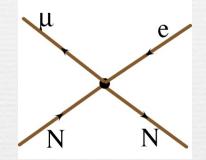


- This type of diagram gives rise to small CLFV through virtual neutrino mixing
- Also contributes to $\mu \rightarrow e \gamma$ if photon real

$$L_{CLFV} = \frac{m_{\mu}}{(\kappa + 1)\Lambda^2} \bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu}$$

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· Fermi Interaction





- Corresponds to exchange of a new, massive flavorchanging neutral current particle $\frac{1}{\Lambda^2} = \frac{f^2}{16\pi^2} \frac{1}{M_{\text{new}}^2}$
- **Does not produce** μ→eγ

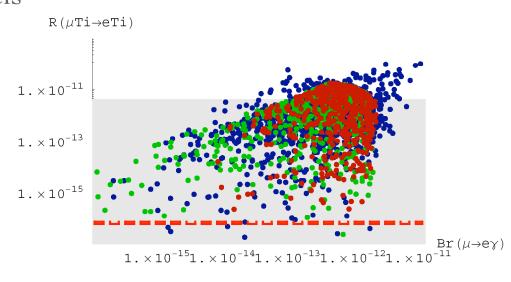
$$\mathcal{L}_{\text{CLFV}} = \frac{m_{\mu}}{(\kappa+1)\Lambda^{2}} \bar{\mu}_{R} \sigma_{\mu\nu} e_{L} F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^{2}} \bar{\mu}_{L} \gamma_{\mu} e_{L} (\bar{u}_{L} \gamma^{\mu} u_{L} + \bar{d}_{L} \gamma^{\mu} d_{L})$$



Combination of μe Conversion and $\mu \rightarrow e \gamma$



- Distinguish by using both: sample Little Higgs Models
- Compare and Contrast to LHC
- Measuring in several channels in several experiments is always better!



 $\mu \rightarrow e \gamma$ conversion in Ti vs $\mu \rightarrow e \gamma$ for Randall-Sundrum, Agashe et al.,

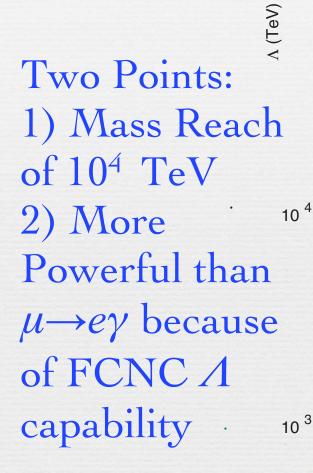
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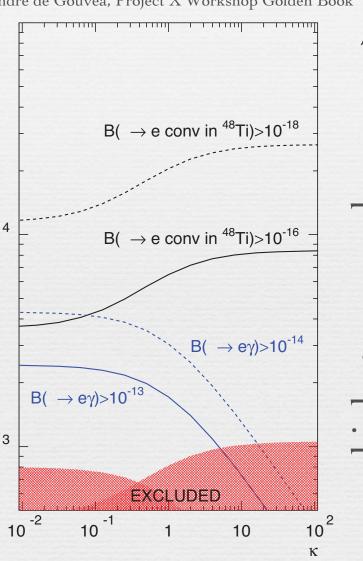
Overview of Reach



André de Gouvêa, Project X Workshop Golden Book



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 Λ four-point, κ penguin

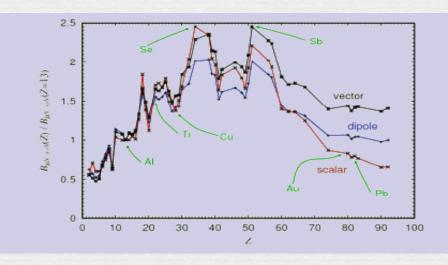
What Do We Measure?

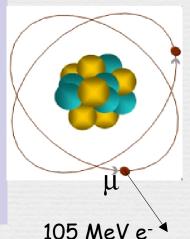


ν μ to e conversion in the field of a nucleus

$$R_{\mu e} \equiv \frac{\Gamma(\mu^{-} + (A, Z) \to e^{-} + (A, Z)}{\Gamma(\mu^{-} + (A, Z) \to \nu_{\mu} + (A, Z - 1))}$$

- Stop muons in target (Z,A)
- Physics
 sensitive to Z:
 with signal, can
 switch target to
 probe source of
 new physics





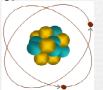
choose Z based on tradeoff between rate and lifetime: longer lived reduces prompt backgrounds
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Backgrounds



Decay-in-Orbit and Radiative μ Capture



$$\mu \to e \nu_{\mu} \nu_{e}$$
 coherent can yield e near endpoint $\mu^{-} \mathrm{Al} \to \gamma \nu_{\mu} \mathrm{Mg}$

$$\mu^{-} \mathrm{Al} \rightarrow \gamma \nu_{\mu} \mathrm{Mg}$$

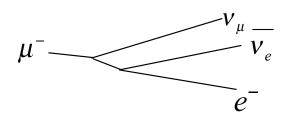
asymmetric conversion yields e near endpoint

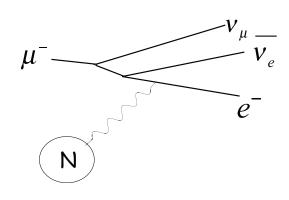
- Prompt, Beam Related
 - extinction, delayed live window $\pi^- \text{Al} \rightarrow \gamma \text{ Mg}$
- Cosmic Rays and Neutrons
 - shielding and veto system
- Antiprotons
 - thin window in transport solenoid R. Bernstein



Decay-in-Orbit Background







- High Rate
- Peak 52.8 MeV
- Detector insensitive to these

- Coherent balance of momentum
- Rate falls as $(E_{\text{max}} E)^5$
 - Extends near Signal
- Drives Resolution NP'08

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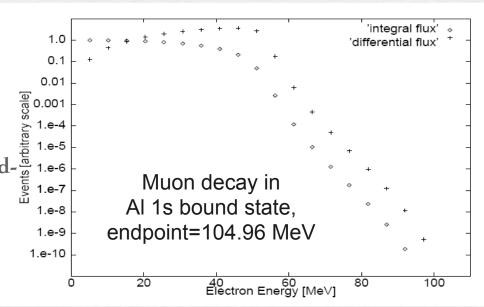




Decay-In-Orbit Details

- Ee(max)= (m_μc² NuclearRecoilEnergy AtomicBindingEnergy)
- For Z=13 (Al), Atomic BE=0.529 MeV, Recoil energy=0.208 MeV →Ee(max) =104.96 MeV
- Rate near the maximum energy falls very rapidly. Near endpoint: proportional to (Ee(max)-E)⁵
- Major potential source of background-Discriminate against it with good electron energy resolution, ~1 MeV FWHM for μ2e

looks exactly like signal except for electron energy



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Prompt Backgrounds



- Prompt: due to beam particles which interact almost immediately when they enter the detector region,
 - Radiative pion capture, $\pi^- + A(N,Z) -> \gamma + X$.
 - $\gamma \rightarrow e^+e^-$; if one electron ~ 100 MeV in the target, looks like signal. Major limitation in SINDRUM II.
 - Beam electrons: incident on the target and scatter into the detector region. Need to suppress e with E>100 MeV near endpoint
 - In-flight muon decays





Existing Limits

- $R_{\mu e} < 6.1 \times 10^{-13}$ in Ti (SINDRUM)
- Want to probe to 10-16 or better
- Factor of $\approx 10^4$ improvement non-trivial

Prompt Cosmic Ray Background Background Expected om tar 10 ³ Signal suppr prompts supr **Muon Decay** in Orbit μ→e conversion at B.R.= 4×10^{-12} ------85 90 120 100 105 110 115 total e energy in (MeV) Experimental signature is 105 MeV e-

originating in a thin Ti stopping target

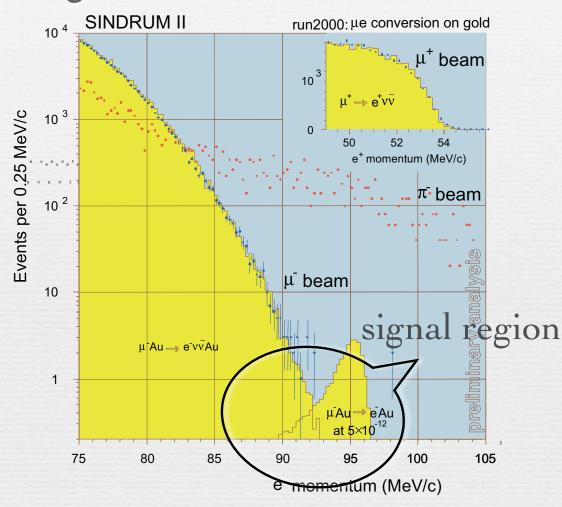
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Scary Plot



- Final
 SINDRUM
 -II on Au
- Note
 Background
 in Signal
 Region
- Multiply
 Problems
 by 10⁴



July 14, 2001

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HEP 2001 (W.Bertl - SINDRUM II collaboration) NP'08







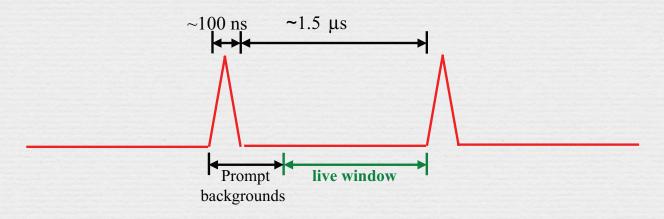
- Improvements:
 - >10³ increase in muon intensity from SINDRUM
 - High Z target for improved pion production
 - Graded solenoidal field to maximize pion capture
 - Curved Transport Solenoid and Pulsed Beam to Eliminate prompt backgrounds
 - must achieve required extinction and measure it
 - Resolution for Decay-In-Orbit Critical





Pulsed Beam

- Beam pulse duration $\ll \tau_{\mu}$, Pulse separation $\approx \tau_{\mu}$
- Large duty cycle
- Extinction between pulses < 10⁻⁹ (assume this for calculations)

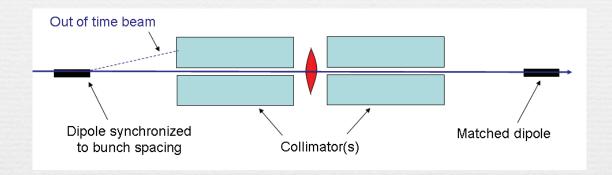




Measuring Extinction



Protons in beam between pulses:



- "Switch" dipole timing to eliminate bunches, accept background for direct measurement
- Other schemes under investigation
 - Measurement: off-angle collimators and telescope? R. Bernstein NP'08





Outline of Remainder

- Beam pre- and post-Project X:
 - how do we get muons to target? how many? time structure?
- Detector:
 - How Do We Achieve Required Rejection and Resolution?

20 kW(current) $200 \,\mathrm{kW}$ (Project X) $2000 \,\mathrm{kW}$ (Project X Upgrades) NP'08

8 GeV Power

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Intensity Summary



point of this slide: if MECO worked, $\mu 2e$ at FNAL works: pre-project X or with Project X

	MECO	Mu2e Booster	Mu2e Project X, no expt. upgrade	Mu2e Project X, expt. upgrade
protons/sec	40x10 ¹² (design)	18×10^{12}	70×10^{12}	160×10^{12}
average beam power	50 kW (design)	$23~\mathrm{kW}$	90 kW	$200~\mathrm{kW}$
duty factor	0.5 s on, 0.5 s off, 50%	90%	90%	90%
instantaneous rate	80x10 ¹² (design)	20×10^{12}	$77x10^{12}$	220×10^{12}
short term beam power	100 kW (design)	25 kW	100 kW	$220~\mathrm{kW}$
Beam pulse period, msec	1.35	1.65	1.65	1.65
Data collection time interval msec	0.7-1.35	0.7-1.65	0.7-1.65	0.7-1.65

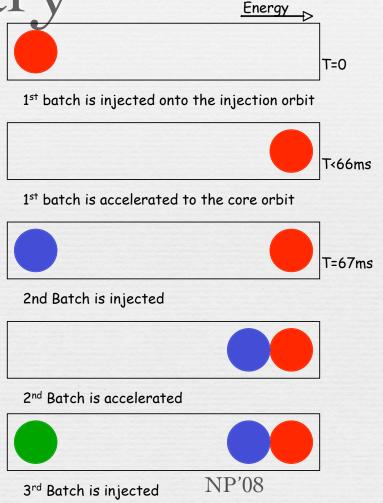






Booster:

- The Booster accelerates protons from the 400 MeV
- Accumulator:
 - momentum stacking successive pulses of antiprotons now, 8 GeV protons later
- Debuncher:
 - smooths out bunch structure to stack more \overline{p}
- Recycler:
 - holds more \overline{p} than Accumulator can manage, "store" here R. Bernstein





Overall Scheme



- Now:
 - Booster-MI-Recycler
 - MI is limiting since must load MI fully before accelerating to 120 GeV
- In NovA/μ2e era:
 - Booster-Recycler and slip-stacking
 - Load into Recycler while accelerating in MI
- In Project X Era:
 - Linac-Recycler
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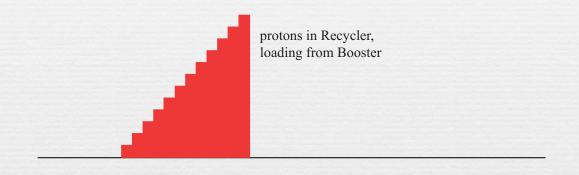
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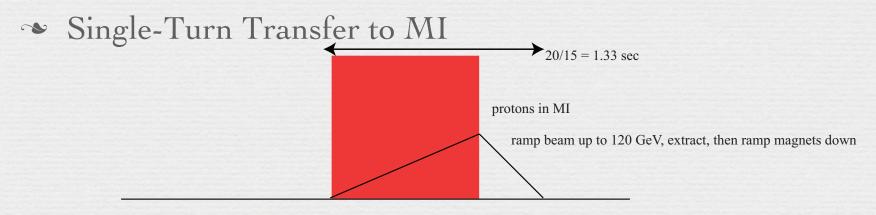
NovA Era



In order to increase protons to the NOvA neutrino experiment after the collider program ends, protons will be "stacked" in the Recycler while the

Load from Booster to Recycler

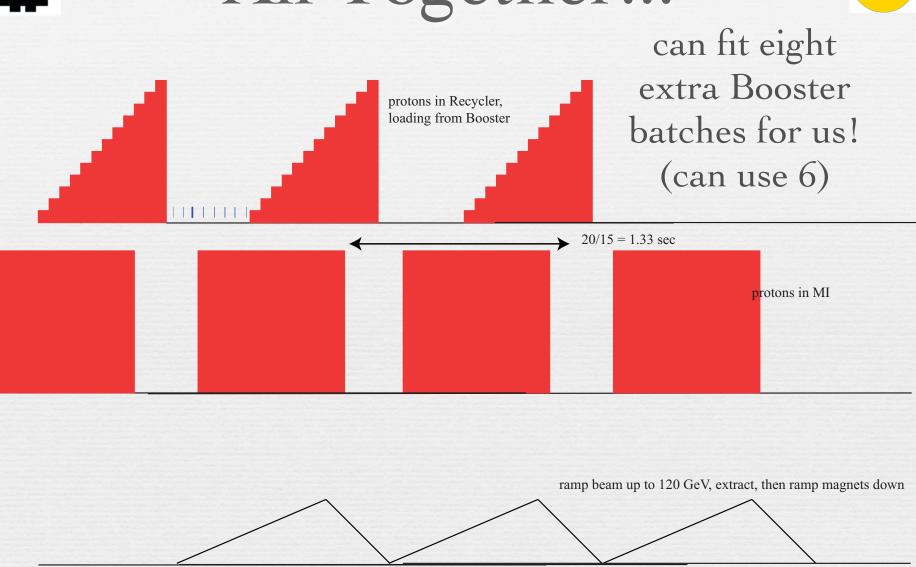






All Together...

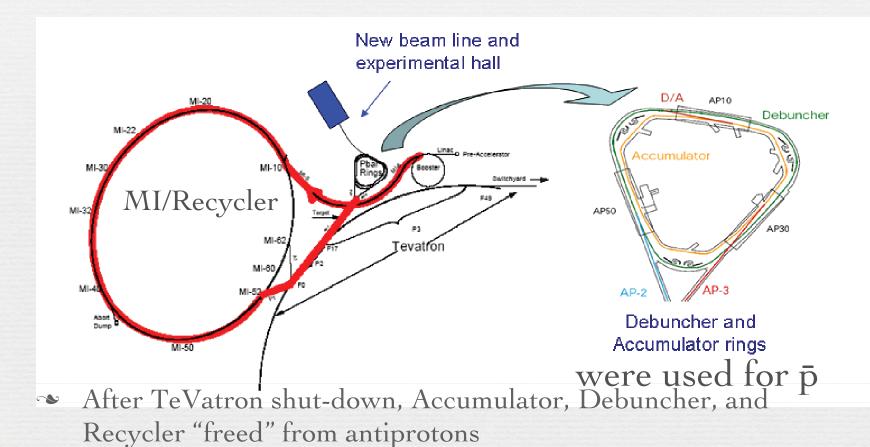






Booster-Era (before Project X)





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"Boomerang Scheme"

- Booster Batches transported partway through Recycler and injected directly into Accumulator
- "Momentum-Stack" batches in Accumulator
- Transfer to Debuncher
- Rebunch into Single Bunch:
 - → 38 nsec RMS, ±200 MeV
- Slow Extraction: transverse, yields bunch "train"

Distrumetron Debuncher and Accumulator rings

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Numerically,



- can get 8 Booster Batches every 1.33 sec MI cycle, or 4.8E20/yr (4E12/Booster Batch) from Booster
 - currently 10.5 Hz in Booster, need 15 Hz
 - limits of Booster RF and radiation can be overcome with some work to achieve this
- # of batches limited by longitudinal emittance in A/D to 6 of 8 (84 x .038 ev-sec)
 - Assume $3.6E20 = (6/8 \times 4.8)$ in planning
- This manipulation can produce out-of-bucket beam
- extinction is important: must be controlled and measured

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Project X Upgrades

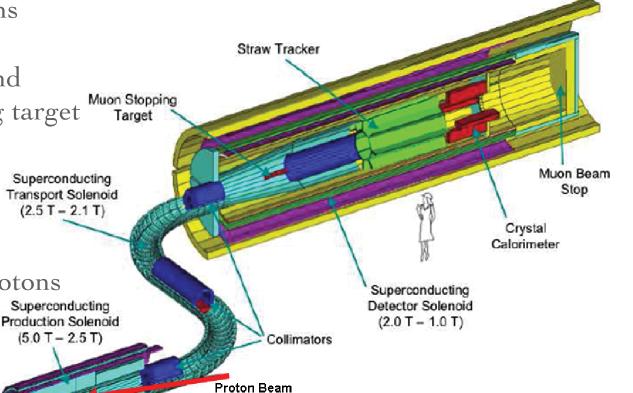


- Ultimate sensitivity would be provided by Project X linac as proton source
 - Deliver up to 200 kW average beam current:
 - ~3 x 10¹⁴ protons/sec at 8 GeV (x10 previous slide)
 - 9mA, 1 msec, 5 Hz
- Three Upgrades for x10 from 200 kW to 2000 kW at 8 GeV:
 - Increase Pulse Length
 - Increase Repetition Rate
 - Increase Number of Klystrons
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need to understand how to push single-event sensitivity to use additional capability

Overview of Experiment

- Magnetic bottle trapping backward-going pions
- Decay into muons and transport to stopping target
- "S"-curve eliminates Superconducting Transport Solenoid backgrounds (2.5 T - 2.1 T)
- Absorbers for antiprotons
- Tracking
- Crystal Calorimeter



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Pion Production Target

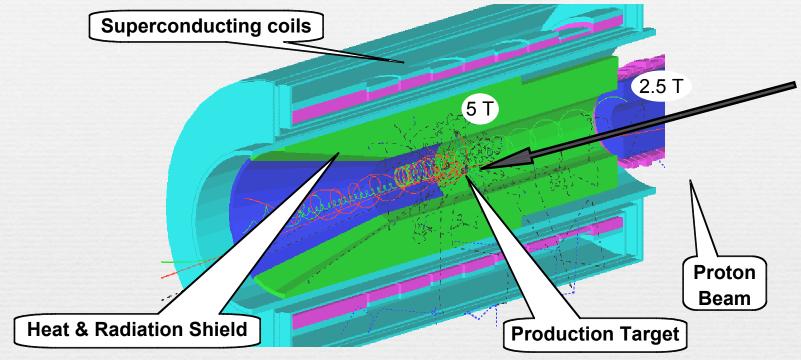
Superconducting

(5.0 T - 2.5 T)



Production Region





- Axially graded 5 T solenoid captures low energy backward and reflected pions and muons, transporting them toward the stopping target
- Cu and W heat and radiation shield protects superconducting coils from effects of 50kW primary proton beam: need upgrade from MECO design for > 50 kW

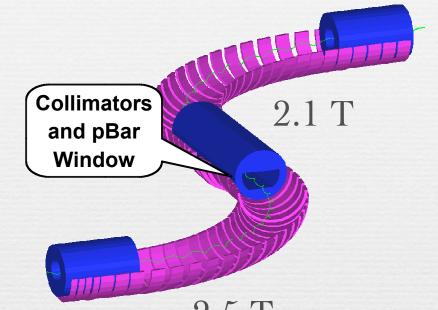
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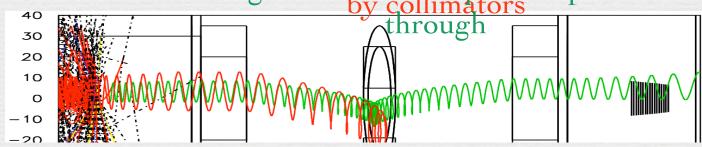
Transport Solenoid



- Curved solenoid eliminates line-of-sight transport of photons and neutrons
- Curvature drift and collimators sign and momentum select beam
- dB/ds < 0 in the straight sections to avoid trapping which would result in long transit time



low momentum particle blocked higher momentum particle passes by collimators



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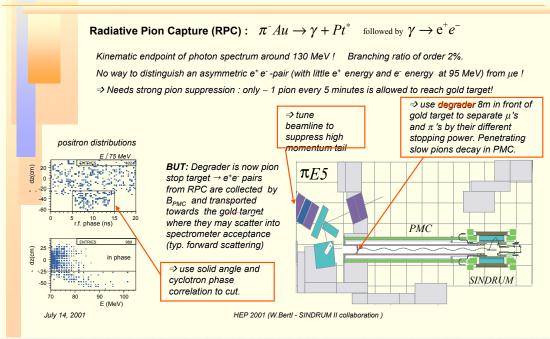


Key Improvement of Both COMET and μ2e



EE FAUL SCHERRER INSTITUT

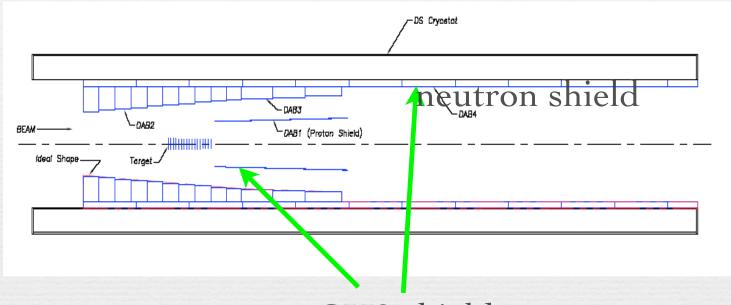
Background: b) pion induced



Curved
Transport
Solenoid in both
modern expt's







CH2 shields

- Conical Shield Reduces background and high rate from protons produced in stopping target
- Outer shield absorbs neutron cloud

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Detector



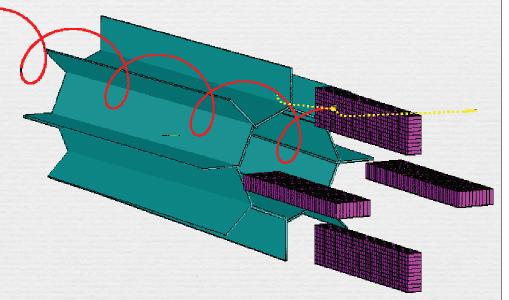
Octagon and Vanes of Straw
Tubes
28

 σ = 200 μ transverse, 1.5 mm axially

- 2800 axial straw tubes, 2.6 m by 5 mm, 25 μ thick
- Immersed in solenoidal field, so particle follows near-helical path

use return yoke as CR shield

- dE/dx, scattering, small variations in field
- Particles with $p_T < 55$ MeV do not pass through detector, but down the center



Followed by Calorimeter

 $\sigma/E = 5\%$, 1200 3.5 X 3.5 X 12 cm PbWO₄

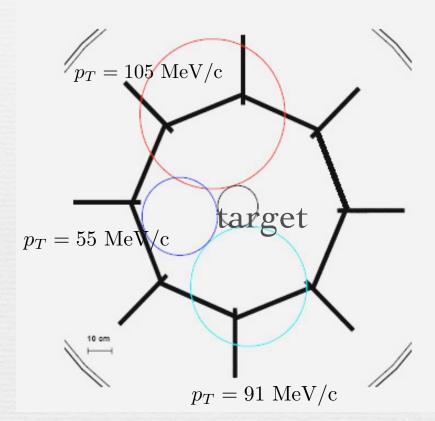
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Beam's Eye View



- Below p_T = 55 MeV, electron stays inside tracker and is not seen
- Looking for helix as particle propagates downstream
- More "vanes" fire as momentum increases



Note: <0.3% of e- from DIO have pt>55 MeV/c

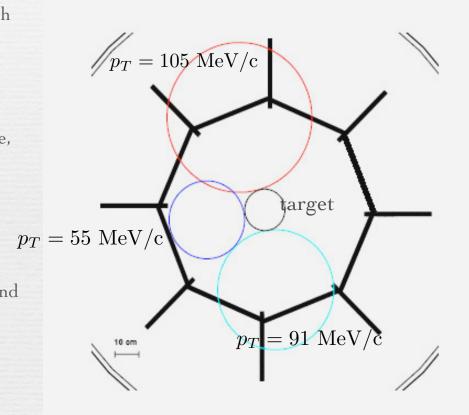
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Details



- 38 -70 cm active radius
- Geometry: Octagon with eight vanes, each ~30 cm wide x 2.6 m long
- Straws: 2.9 m length 5mm dia., 25 mm wall thickness to minimize multiple scattering 2800 total
- Three layers per plane, outer two resistive, inner conducting
- Pads: 30 cm 5mm wide cathode strips affixed to outer straws 16640 total pads
- Position Resolution: 0.2 mm (r,φ) X 1.5 mm (z) per hit is goal
- Energy loss and straggling in the target and multiple scattering in the chambers dominate energy resolution of 1 MeV FWHM



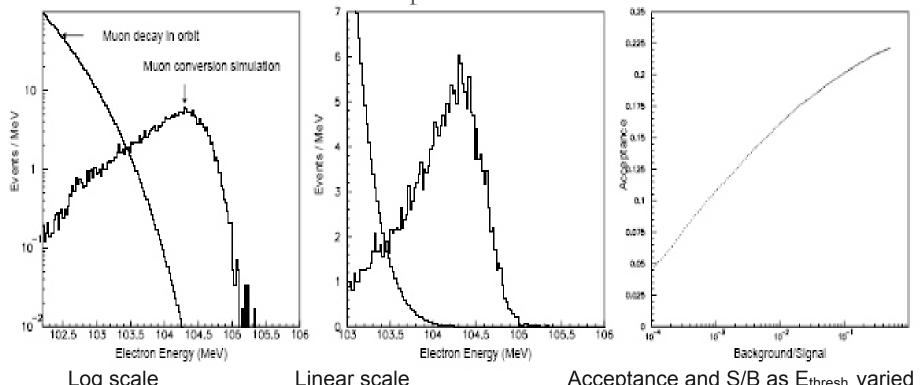


Decay-In-Orbit



R_{eμ}=1x10⁻¹⁶, Energy resolution 1 MeV (FWHM)





Log scale

Acceptance and S/B as Ethresh varied

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Other Backgrounds



- Delayed: due to beam particles which take > ~ few hundred nanoseconds before they produce signals in the detectors on average
 - Protons, neutrons, gammas from muon capture
 - Photons from radiative muon capture
- Antiproton annihilations along beam line or near target- (none in SINDRUM II, potential problem for $\mu 2e$)
- Cosmic Rays- Back/Signal proportional to (run time)/(beam intensity) (can measure off-spill) (x4 MECO)

Some of Backgrounds...



Type	Description	
e_t	beam electrons	
n_t	neutrons from muon capture in muon stopping target	
γ_t	photons from muon capture in muon stopping target	
p_t	protons from muon capture in muon stopping target	
$e(DIO)_t < 55$	DIO from muon capture in muon stopping target, $< 55 \text{ MeV}$	
$e(DIO)_t > 55$	DIO from muon capture in muon stopping target, $> 55 \text{ MeV}$	
n_{bd}	neutrons from muon capture in beam stop	
γ_{bd}	photons from muon capture in beam stop	
$e(DIO)_{bd} < 55$	DIO from muon capture in beam stop, $< 55 \text{ MeV}$	
$e(DIO)_{bd} > 55$	DIO from muon capture in beam stop, $> 55 \text{ MeV}$	
e(DIF)	DIO between stopping target and beam stop	

bd = albedo from beam stop

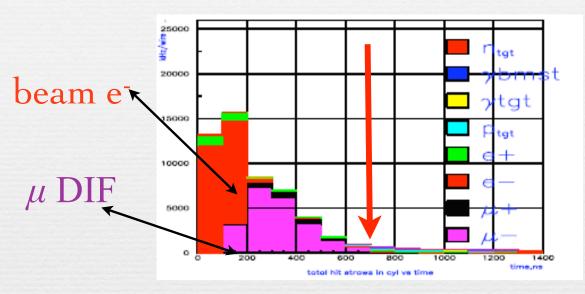
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Backgrounds vs. Time

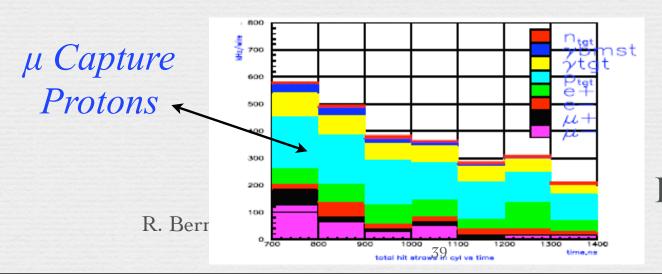


700 nsec



0 - 1400nsec

Rate (MHz)



700-1400 nsec Rate (kHz)





Source	Method	
Energy Resolution	$\pi^+ \rightarrow e^+ v_e$ with reduced field	
Misreconstructed Tracks	Relax calorimeter/ track agreement	
False Tracks (from extra hits)	Allow missing hits, and measure "single hit" rate	



Rates In Tracker



- Rates at *Beginning* of > 700 nsec Time Window, so these are highest
- Rates are manageable: (1/4 of MECO instantaneous)

Type	Rate(Hz)	\mathcal{P} hit	Mean N hits/bkg part	R _{wire} (kHz)
e_t	0.62×10^{11}	0.00032	1.54	16.3
n_t	0.62×10^{11}	0.000142	2.887	12
γ_t	0.62×10^{11}	0.000248	4.524	33.4
p_t	4.5×10^{9}	0.00362	6.263	50.
$e(DIO)_t < 55$	0.2×10^{11}	9.8×10^{-5}	1.44	1.4
$e(DIO)_t > 55$	0.5×10^{8}	0.00127	22.7	0.5
n_{bd}	0.12×10^{11}	7.1×10^{-5}	5.0	1.5
γ_{bd}	0.12×10^{11}	8.3×10^{-5}	4.5	1.5
$e(DIO)_{bd} < 55$	0.5×10^{11}	8.9×10^{-5}	1.	1.65
$e(DIO)_{bd} > 55$	1.4×10^{8}	1.82×10^{-4}	1.5	0.0125
e(DIF)	0.69×10^{6}	1	35.84	8.6
total				116

Calculating Signal Rate



Source	Factor
Running Time (sec)	1.1×10^{7}
Proton Flux (Hz)	3.6×10^{13}
μ entering transport solenoid / incident proton	0.0043
μ Stopping Probability	0.58
μ Capture Probability (normalization process)	0.60
Fraction of Capture in Time Window	0.49
Electron Trigger Efficiency	0.90
Geometrical Acceptance, Reconstruction, etc	0.19
Detected Events for $R_{\mu e} = 10^{-16}$	5.0

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Final Backgrounds

- For $R_{\mu e} = 10^{-16}$ expect 5 events to 0.5 bkg
- Extinction factor of 10-9

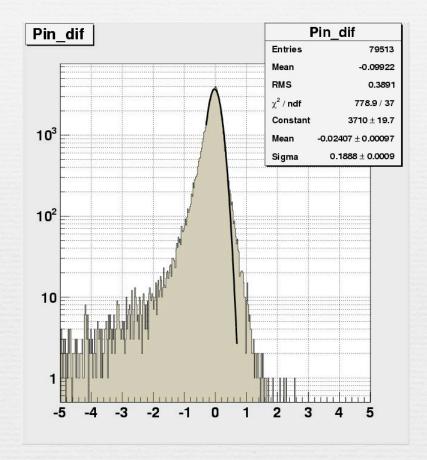
5 signal

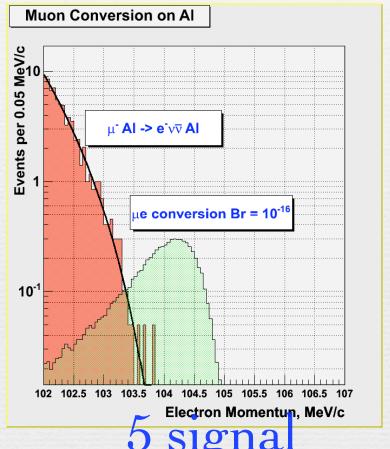
Source	Number/ 4 x 10 ²⁰
DIO	0.25
Radiative π capture	0.08
Scattered e-	0.04
μDIF	0.08
π DIF	<0.004

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Summary of Capabilities 2







Resolution and Sensitivity



Cost and Schedule ~\$100M ~2014



- A detailed cost estimate of the MECO experiment had been done just before it was cancelled:
 - Solenoids and cryogenics: \$58M
 - Remainder of experimental apparatus: \$27M
 - Additional Fermilab costs have not been worked out in detail.

 Recent Project X era planning exercise gives ~ \$130M total cost.
- Hope to begin Accelerator work along with NOvA upgrade ~2010 (or 2011 if Run II extended)
 - Based on the original MECO proposal, we believe the experiment could be operational within five years from the start of significant funding
 - Driven by magnet construction.
- With the proposed beam delivery system, the experiment could collect the nominal 4×10^{20} protons on target in about one to two years, with no impact on NOvA

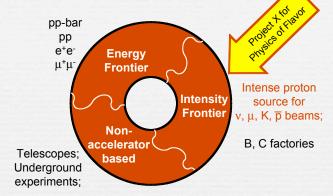
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Tools for Particle Physics



Conclusions



- The μ 2e experiment is an important measurement!
- In the initial phase (without Project X) we would either:
 - Reduce the limit for $R_{\mu e}$ by more than four orders of magnitude $(R_{\mu e} < 6 \times 10^{-17} \ @ 90\% \ C.L.)$
 - Discover unambiguous proof of Beyond Standard Model physics
- With a combination of Project X and/or improved muon transport, we could either
 - Extend the limit by up to two orders of magnitude
 - Study the details of new physics

R. Bernstein





Backup Slides

- Synergies with Neutrino Factory
- Cosmic-Ray Shield
- Acceptance of Calorimeter

Synergies with Neutrino Factory?

- There are a number of synergies between this project and muon cooling efforts
- The Debuncher beam could be extracted in a single turn to produce the short, intense bunch needed by muon production experiments
- Muon cooling studies have increased the understanding of solenoidal transport.
- It is possible that a "helical cooling channel", of the sort envisioned for muon cooling, could generate a significantly higher muon yield for this experiment.
- We will investigate these in more detail for the proposal.
- A combination of increased flux from Project X and a more efficient muon transport line could potentially result in a sensitivity as low as 10⁻¹⁸



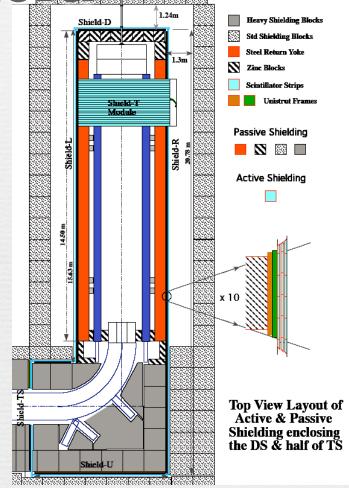
Cosmic Ray/Neutron



Shield

- Two Layers of Scint
 - OR

- Inefficiency ≤ 10⁻⁴
- Neutrons (from beam)





Acceptance of Calorimeter



- Note Log
 Scale
- High-Energy
 Tails of DIO
 do not swamp
 trigger

